What were Ampère's Earliest Discoveries in Electrodynamics?

*By L. Pearce Williams**

IN SEPTEMBER AND OCTOBER 1820, André-Marie Ampère read a series of memoirs to the Paris Académie des Sciences in which he laid out the basic physics of the new science of electrodynamics. These were well-attended sessions whose contents were reported by a number of people, including Ampère. There is, nevertheless, considerable confusion among modern historians of science over both the order and content of Ampère's reports and discoveries. Briefly, I have argued that Ampère's mind leapt directly from a consideration of the interaction of an electrical current and a compass needle reported by Hans Christian Oersted earlier in 1820 to the conclusion that two current-carrying wires must interact, and from thence to the idea that helices would act like magnets.[1] Alfred Kastler, on the other hand, writes that it was the identical action of helices and magnets that led Ampère to the mutual effects of current-carrying wires. R. A. R. Tricker implies that these discoveries were simultaneous.[2]

It is the aim of this paper to reduce this confusion and, by a close and critical reading, to offer an exact chronology of ideas and discoveries which Ampère reported in the weeks immediately following his first communication to the Académie des Sciences on 18 September 1820.

THE SOURCES

The *Procès-verbaux* of the sessions of the Académie do little more than announce that Ampère read a memoir, but they do establish a rough chronology.[3]

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[1] L. Pearce Williams, *Michael Faraday: A Biography* (London/New York, 1965), p. 143; see also Williams, s.v. "Ampère," in *The Dictionary of Scientific Biography*, Vol. I (New York: Scribners, 1970), p. 143.

[2] Alfred Kastler, "Ampère et les lois de l'électrodynamique," *Revue d'histoire des sciences*, 1977, *30*:146; R. A. R. Tricker, *Early Electrodynamics: The First Law of Circulation* (Oxford, 1965), p. 27.

[3] Institut de France: Académie des Sciences, *Procès-verbaux des séances de l'Académie tenues depuis la fondation de l'Institut jusqu'au mois de Août 1835*, 10 vols. (Paris: Hendaye, 1910–1922), Vol. VII (1916) (***Procès-verbaux***). For all mention of Oersted's discovery and its development in France through November 1820, see pp. 83, 90, 94, 95, 97–101. (Abbreviations used for the major sources are given in boldface in the notes to this section for ease of cross-reference.)

The *Bibliothèque universelle,* published in Geneva and edited by Ampère's friend, August de la Rive (among others) regularly printed accounts of the sessions of the Académie in Paris, as did many other journals of the time. The reporter for the *Bibliothèque* provides particularly valuable accounts of Ampère's presentations.[4]

Ampère often sent copies of his remarks or of early versions of his memoirs to editors of journals to be used as the editors saw fit. Such a report was published verbatim in the *Annales générales des sciences physiques,* a Belgian journal that reported faithfully on the activities of the Paris Académie. The beginning of the article is set off by quotation marks, indicating that the editors are reproducing what Ampère had sent them. A footnote informs us that Ampère's presentation was cut short before he could read the third paragraph, so what we have is what Ampère intended to read on 18 September but could not complete. It is, therefore, our most accurate source for this meeting.[5]

The most important source for Ampère's early discoveries is the memoir that he wrote in the autumn of 1820. It is this memoir which has provided historians with most of the facts concerning these discoveries, and it is also this memoir which is the source of most of the confusion over the sequence of both facts and ideas in Ampère's works. It is, therefore, necessary to discuss this source in some detail.

The memoir appeared in two parts in separate issues of the *Annales de chimie et de physique* in early 1821. Part I is entitled, "Mémoire présenté à l'Académie royale des Sciences, le 2 octobre 1820, où se trouve compris le résumé de ce qui avait été lu à la même Académie les 18 et 25 septembre 1820, sur les effets des courans électriques."[6] The second part appeared in a later issue with the title, "Suite du Mémoire sur l'Action mutuelle entre deux courans électriques, entre un courant électrique et un aimant ou le globe terrestre, et entre deux aimans."[7] The two memoirs were published in separate form at about the same time with the title "Mémoires sur l'action mutuelle de deux courans électriques,

[4] *Bibliothèque universelle des sciences, belles-lettres, et arts, faisant suite à la Bibliothèque Brittanique,* 1821, *17*:78–84 (September meetings), 251–248 (October, November, and December meetings) (***Bibl. universelle***). The reports in *Annales de chimie et de physique,* of which Ampère's close friend François Arago was an editor, however, do not present an accurate and detailed account of what Arago recognized as a series of discoveries of fundamental importance, but merely refer the reader to Ampère's published account (itself not an accurate historical document: see note 7 and discussion); see *Ann. chim. phys.,* 2^{e} series, 1820, *15*:82 (***Ann. chim. phys.***).

[5] "Analyse des Mémoires lus par M. Ampère à l'Académie des sciences, dans les séances des 18 et 25 septembre, des 9 et 30 octobre 1820," *Annales générales des sciences physiques* (published only 1819–1821), 1820, *6*:238–257 (**"Analyse"**); see p. 241. To my knowledge, this is the first time that this source has been used to throw light on Ampère's early discoveries.

[6] **"Mémoire sur les effets,"** *Ann. chim. phys.,* 1820, *15*:59–76; **"Suite du Mémoire,"** *ibid.,* pp. 170–218.

[7] *Mémoires sur l'action mutuelle de deux courans électriques, sur celle qui existe entre un courant électrique et un aimant ou le globe terrestre, et celle de deux aimans l'un sur l'autre.* French savants regularly republished their articles from learned journals as separate pieces, often with significant alterations. This considerably altered offprint is announced in *Bibliographie de la France,* 23 Mar. 1821, *10*:156, item 1115; it was sent, *inter alia,* to Faraday, and a copy exists in the library of the Royal Institution. *Bibliographie de la France,* the weekly and contemporary account of French publications, does not provide an accurate date for the appearance of any given publication; the editor eventually lists most of Ampère's works, even pamphlets, produced in France, but there is often a time lag. (See note 15 for a publication with a specific date that is not the date at which the announcement is made in *Bibliog. France.*) On the difficulties of Ampère's bibliography, see R. Taton, "Repères pour une biographie intellectuelle d'Ampère," *Rev. Hist. Sci.,* 1978, *31*:233–248.

sur celle qui existe entre un courant électrique et un aimant ou le globe terrestre, et celle de deux aimans l'un sur l'autre," and described as an "Extrait des *Annales de Chimie et de Physique*." This is not quite accurate, for Ampère took the opportunity, as was his habit, to make considerable changes in the offprint. This memoir then served as the basis for another reprint in the collection *Recueil d'Observations électro-dynamiques,* which itself appeared in two editions, one of 1822 and a larger one in 1823.[8] Finally, the Société de Physique used the memoir from the 1823 *Recueil* in the two-volume *Mémoires sur l'électrodynamique* edited by J. Joubert and published in 1885 and 1887.[9] All citations in this paper will come from the original memoir as it appeared in the *Annales de chimie et de physique.*

The confusion among historians arises from a number of aspects of this memoir. The basic cause lies in the confusion in Ampère's mind. At the best of times, his thoughts were unorganized. In 1823, Hans Christian Oersted visited Paris and wrote his wife about his meetings with Ampère:

> The conversation mostly turned upon scientific matters and I had a long discussion with Ampère about magnetism. He is a very unskillful debater and neither understands clearly how to comprehend the arguments of others nor how to set forth his own, nevertheless he is a profound thinker. . . . On the 10th [February] I was at Ampère's by appointment to see his experiments. He had invited not a few. . . . He had three considerable galvanic apparatus ready, his instruments for showing the experiments are very complex, but what happened? Hardly any of his experiments succeeded. . . . He is dreadfully confused and is equally unskilled as an experimenter and as a debater.[10]

In September and October 1820, Ampère's habitual confusion was exalted by his excitement over his new discoveries. Ideas flashed through his mind with such rapidity that he had barely time to note them down on scraps of paper before he set off chasing new ones. As he wrote to his friend Roux-Bordier: "Je sais bien que mon mémoire n'est pas rédigé assez clairement; cela vient de ce que je l'ai écrit avec une hâte extrême et par morceaux détachés que j'ai ensuite réunis comme j'ai pu."[11] The result is that this memoir is almost entirely untrustworthy as a source for the historical sequence of either Ampère's ideas or his discoveries.

The final source of confusion raises a rather delicate point. The title of the

[8] The first edition, *Recueil de mémoires, notices, extraits de lettres ou d'ouvrages périodiques sur les sciences, relatifs à l'action mutuelle de deux courans électriques, sur celle qui existe entre un courant électrique et un aimant ou le globe terrestre, et celle de deux aimans l'un sur l'autre* (Paris, 1822), is a very rare work of some 318 pages which Kenneth Caneva (to whom I owe this reference) tells me exists to his knowledge only in the Teylers Museum in Haarlem, the Netherlands. (It is probably to this work that a note on the flyleaf of the 1823 edition refers as a defective edition.) The 1823 edition contains 360 pages, and the date of publication on the copies at Cornell and the Bibliothèque Nationale is 1822; but Prof. Caneva assures me that the proper date of publication is 1823.

[9] *Mémoires sur l'électrodynamique,* Vols. II and III of *Collection de Mémoires relatifs à la physique,* 5 vols. (Paris: Société de Physique, 1885–1887).

[10] *Breve fra og til Hans Christian Ørsted udgivne of Mathilde Ørsted,* 2 vols. (Copenhagen, 1870), Vol. II, pp. 53, 51; as cited in Kirstine Mayer, "The Scientific Life and Works of H. C. Ørsted," in Hans Christian Ørsted, *Scientific Papers,* ed. K. Mayer, 3 vols. (Copenhagen; Høst, 1920), p. cxiv.

[11] Ampère to Roux-Bordier, 21 Feb. 1821; in *Correspondance du Grand Ampère,* ed. L. de Launay, 3 vols. (Paris: Gauthier Villars, 1936–1943), Vol. II, p. 566.

first part, used *only* in the *Annales* version, states explicitly that this part is a summary of what Ampère read to the Académie des Sciences on 18 and 25 September and that the memoir was presented to the Académie on 2 October. The first statement is simply not true, as will be proved in the course of this article. The *Procès-verbaux* of the Académie makes no mention of the presentation of this memoir on 2 October, and I confess to some doubts that it was presented then.[12] My doubts are based on the fact that Ampère discusses the attractions and repulsions of two rectilinear, parallel current-carrying wires, a discovery that he did not announce to the Académie until 9 October. As we shall see, this effect is recorded by one source as being noticed at the very end of the 25 September session, so Ampère might very well have worked on it feverishly after that session and composed the memoir in time to hand it in on 2 October. It is unlike Ampère, however, to let time go by before announcing such an important discovery. In a similar vein, I will argue that the section in the second part of this memoir in which Ampère explicitly states that he is simply transcribing what he said in the session of 18 September is demonstrably untrue. Again, the second paragraph clearly implies that Ampère had discovered the mutual effects of two current-carrying wires by 18 September.[13]

This rather lengthy discussion of Ampère's memoir will, I trust, convince readers that it cannot be used to establish chronology.

Ampère's correspondence is our most important source for establishing precise dates, especially for his earliest discoveries and ideas. The published *Correspondance,* unfortunately, is not terribly trustworthy, for De Launay omitted large numbers of letters and mistranscribed many of those he included.[14] For the purposes of this paper, however, the *Correspondance* is sufficiently accurate.

There are, finally, a number of "histories" to which Ampère either contributed or of which he approved that permit the reconstruction of key events. The September issue of the *Journal de physique* contained an article by Hachette summarizing Oersted's and Ampère's early discoveries to which Ampère appended his own notes on the lectures that he had given to the Académie des Sciences from 18 September through 13 November.[15] Similarly, Ampère appended two notes to an account that appeared in the *Annales des mines* by Gillet de Laumont in 1820.[16] In early spring 1821, Ampère summarized his early work in an essay that appeared both in the *Bibliothèque universelle* and in J.-B. J.

[12] By "presenté" Ampère means to convey that he handed a copy of the memoir to the presiding officer at the 2 Oct. meeting. (He certainly did *not* read the memoir to the Académie for if he had, the title would have followed his customary usage and read "lu.")

[13] "Suite du Mémoire," pp. 196 ff.

[14] See Taton, "Repères," for some of these points.

[15] "Notes de M. Ampère sur les lectures qu'il a faites à l'Académie des Sciences (**"Notes"**), *Journal de Physique,* 1820, *91*:166–169, immediately following (J.-N.-P.) Hachette, "Sur les expériences électro-magnétiques de Mm. Oersted et Ampère," *ibid.,* pp. 161–166. Here the "reprint" may have appeared before the journal article: *Bibliog. France* announced *J. Phys.,* 1820, *91,* on 20 Jan. 1821, *10*:42, item 279; the "reprint" on 2 Dec. 1820, *9*:677, item 4443. "Notes" is also available in Christine Blondel, "Sur les premières recherches de formule électrodynamique par Ampère (octobre 1820)," *Rev. hist. sci.,* 1978, *31*:53ff, as "Appendice I."

[16] "Note sur les expériences Électro-magnétiques de MM. Oersted, Ampère et Arago relatives à l'identité de l'aimant avec l'électricité," *Annales des mines,* 1820, *5*:535–553 (**"Note sur les expériences"**). For the attribution to Gillet de Laumont, see *Correspondance,* Vol. II, p. 567 (I am grateful to Prof. Caneva for calling this attribution to my attention).

Delambre's history of the works of the Académie for 1820.[17] Another such summary was published in 1822 with Ampère as coauthor with Jacques Babinet.[18]

These, then, are the sources for this paper. From them it is possible to draw a well-documented, coherent, and plausible account of Ampère's discoveries, the chronology of their presentation to the scientific public, and even the course of his ideas.

AMPÈRE'S DISCOVERIES

The story begins on 4 September with François Arago's presentation of Oersted's results announcing the discovery of electromagnetism. All our sources tell us of this meeting is that, in the words of the *Procès-verbaux,* "M. Arago rend compte des expériences faites par M. Oerstedt [sic] relativement à l'*Influence réciproque du magnétisme et du galvanisme,* et répétées à Genève par M. de la Rive."[19] In his introductory footnote to the version of Oersted's paper in *Annales de chimie,* Arago remarked that he was given a copy of the paper that Oersted had sent to Geneva by M.-A. Pictet, so it would seem logical to assume that he either read parts of Oersted's paper to the Académie or used Oersted's paper to describe the effect. In any case, it does seem safe to assume that the basis for what Arago presented to the Académie on 4 September and on 11 September, when he repeated Oersted's experiments, is to be found in Oersted's published paper.[20]

[17] "Exposé sommaire des divers Mémoires lus par Mr. Ampère à l'Académie Royale des Sciences de Paris, sur l'action mutuelle de deux courans électriques, et sur celle qui existe entre un courant électrique et le globe terrestre ou un aimant," *Bibl. universelle,* 1821, *16*:309–319 (**"Exposé sommaire"**) (owing to a misprint, the first page is numbered 209 instead of 309). J.-B. J. Delambre, "Analyse des travaux de l'Académie royale des sciences, pendant l'année 1820: Partie mathématique," in *Mémoires de l'Académie royale des sciences de l'Institut de France, 1819–1920,* Vol. IV (Paris, 1824), pp. cxxxviii–cxlviii, differs only slightly from "Exposé sommaire," and it is obviously by Ampère. See Kenneth L. Caneva, "Ampère, the Etherians, and the Oersted connexion," *British Journal of the History of Science,* 1980, *13*:121–138, on p. 132, n. 3, for full documentation of this point. The "Analyse des travaux" was published separately on 2 April 1821. See A.-M. Ampère, "Notice sur les éxperiences électro-magnétiques de MM. Ampère et Arago, par M. Ampère; lue à la séance publique de l'Académie royale des sciences de Paris le 2 avril 1821," *Bibl. universelle,* 1821, *17*:17: "On . . . trouve une exposition complète dans l'analyse, *publiée aujourd'hui même,* des travaux de l'Académie pendant l'année 1820" (emphasis added). See also the announcement in *Bibliog. France,* 1821, *10*:256, item 1873.

[18] A.-M. Ampère and Jacques Babinet, "Exposé des nouvelles découvertes sur le magnétisme et l'électricité," in J. Riffault, *Supplément à la traduction française de la cinquième édition du système de chimie par Th. Thomson* (Paris, 1822), pp. 168–256, also published separately as *Exposé des nouvelles découvertes sur l'électricité et le magnétisme de MM. Oersted, Arago, Ampère, H. Davy, Biot, Erman, Schweiger, De La Rive, etc.* (Paris, 1822). Since both are quite rare, I shall regularly cite both (as **Riffault, *Supplément,*** and ***Exposé***).

[19] *Procès-verbaux,* Vol. VII, p. 83. Neither the account in *Bibl. universelle, 16*:78, nor that in *Ann. chim. phys.,* 1820, *15*:80, adds to this.

[20] J. Chr. Oersted, "Experimenta circa effectum, etc.; Expériences sur l'effet du conflit électrique sur l'aiguille aimantée," *Ann. chim. phys.,* 2[e] serie, 1820, *14*:417ff. There is some confusion in the sources that illustrates Ampère's almost total lack of chronological sense. Hachette, writing in Nov. 1820 for the Sept. 1820 *J. Phys.,* which appeared in Dec., mentioned that Oersted's experiment "n'est connu à Paris que depuis trois mois" ("Sur les expériences," p. 164). Although Ampère knew perfectly well that Arago had first reported on the effect in early September, he later wrote "On sut à Paris, au mois de juillet 1820, que M. Oersted avait observé en Danemark une action ignorée jusqu'alors entre un conducteur voltaique et un aimant." Ampère to M. Beuchot, Mar. 1824 (according to de Launay; I do not trust either the date or the attribution), *Correspondance,* Vol. II, p. 646. This has apparently led Jacques Merleau-Ponty to suggest that Oersted's experiment was

On 25 September 1820, Ampère wrote his son, Jean-Jacques, that he had been thinking continually of Oersted's effect "depuis que j'ai entendu parler pour la première fois de la belle découverte de M. Oersted." What had attracted Ampère's attention? As Kenneth Caneva shows, Ampère had never been particularly interested in the voltaic pile, and his only recorded earlier treatment of electricity and magnetism dates back to his years as a teacher at Bourg-en-Bresse in the Ecole Centrale there. Caneva then argues that it was because Ampère was committed to a world view in which the ether played a central role that he leaped at Oersted's discovery.[21]

I think that later the possibility of explaining electrodynamics in etherial terms and his friendship for both Fresnel and Arago reinforced Ampère's commitment to the study of the relations between electricity and magnetism. But on 10 September 1820 these do not appear to have been factors. In a footnote at the very beginning of the *Exposé,* Riffault states that Ampère, after having heard of Oersted's discovery, "s'empressa de s'occuper de diverses expériences à ce sujet, dans la seule vue d'abord de compléter le travail du savant professeur danois." Riffault could have known this only from Ampère and, since his first results, as reported to the Académie des Sciences do, in fact, complete the work begun by Oersted, I think we may have some confidence that this truly represents Ampère's motives.[22]

What does "compléter le travail" mean when applied specifically to Oersted's paper? I should like to suggest that what caught Ampère's attention was the description of what happened when a compass needle was held over or under a current-carrying wire: "Si le fil n'est pas à plus de trois quarts de pouce de l'aiguille, la déclinaison de celle-ci fait un angle d'environ 45 degrés. Si l'on augmente la distance, l'angle décroit à proportion. D'ailleurs, la quantité absolue de cette déviation varie selon que l'appareil est plus ou moins puissant."[23] Such variations in the deviation of the compass needle and even its setting at 45 degrees made no physical sense. Ampère realized that the true nature of the effect could not be observed until the force of terrestrial magnetism was somehow neutralized, for what Oersted clearly had observed and reported on was the resultant of the force from the wire and that from the earth's magnetic field. Ampère now set out to discover, as precisely as possible, the character of the force emanating from the wire alone. We can follow him by turning to the "Analyse," the verbatim report in the *Annales générales.*

According to the editors of the *Annales générales,* the memoir that Ampère read on 18 September consisted of only three paragraphs. Moreover, time was short so that he did not get to read the third paragraph until the next meeting of the Académie on 25 September.[24] In the first paragraph, Ampère reported on

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performed by Gaspard de la Rive in Paris in June 1820: see Merleau-Ponty, *Leçons sur la génèse des théories physiques: Galilée, Ampère, Einstein* (Paris: Vrin, 1974), p. 75. But Caneva, "Ampère," p. 134, n. 23 has shown conclusively that no one in Paris had heard of Oersted's experiment in July 1820.

[21] Caneva, "Ampère," pp. 123ff; Ampère to J.-J. Ampère 19–25 Sept., *Correspondance,* Vol. II, p. 562.

[22] Riffault, *Supplément,* p. 168; *Exposé,* p. 3. The same phrase is used in "Exposé sommaire," which we know was by Ampère (see n. 17 above).

[23] Oersted, "Experimenta: Expériences," p. 420.

[24] "Analyse," pp. 238, 241n.

the results of his experiments; in the second, he described the apparatus that he had used to obtain these results. The first result dealt with the directive action of the force from the current-carrying wire on a compass needle. In order to observe this without interference from the earth's magnetic field, Ampère devised his astatic needle, which effectively eliminated this source of error. The results are set off by quotation marks in "Analyse" and appear to be Ampère's own words:

> I^er^ résultat; action directrice. Lorsqu'un aimant et un conducteur galvanique agissent l'un sur l'autre, et que l'un d'eux, étant fixe, l'autre ne peut que tourner dans un plan perpendiculaire à la plus courte distance du conducteur et de l'axe de l'aimant, celui qui est mobile tend à se mouvoir de manière que les directions du conducteur et de l'axe de l'aimant forment un angle droit et que le pôle de l'aimant qui regarde habituellement le nord soit à gauche de ce qu'on a nommé le courant galvanique, et le pôle sud à sa droite. Bien entendu que la ligne qui mesure la plus courte distance du conducteur et de l'axe de l'aimant rencontre la direction de cet axe entre les deux pôles.

Ampère's first discovery, made sometime between 4 and 18 September, was that a compass needle will set at 90 degrees to a current-carrying wire.[25] This partially "completed the work of the Danish professor."

Ampère's first discovery did not lead immediately to his second. Instead, as the "Analyse" reports, "il a été conduit à l'explication dont il donne les bases dans le troisième paragraphe, et que c'est de cette explication qu'il a déduit ce second résultat géneral":

> M. Ampère . . . arrive à sa théorie de la manière suivante: il remarque que l'ordre dans lequel on découvre deux faits ne doit point influer sur leurs conséquences. Il peut donc supposer qu'on a découvert, d'abord l'action directrice du courant sur l'aiguille, et ensuite l'action du globe. Dans cet ordre de choses on aurait vu en même-temps l'aiguille se diriger par l'influence du courant galvanique et ce courant être la cause de la direction, c'est-à-dire qu'on aurait vu en même-temps l'effet et la cause. Observant ensuite que l'aiguille se dirige aussi par l'action de la terre, on aurait conclu que la cause était le même, et qu'il y avait aussi un courant galvanique autour de la terre, allant de l'est a l'ouest perpendiculairement au méridien magnétique. Admettant donc l'existence d'un pareil courant, M. Ampère croit qu'il est principalement causé par le mouvement de rotation de notre planète et qu'il est modifié par le développement électrique qui s'opère essentiellement entre les substances hétérogènes des couches terrestres.[26]

What led Ampère to this conclusion? The "Analyse" and Ampère himself, in the "Suite du Mémoire," present it as a logical, mental step to be taken from the observation of Oersted's effect. But Ampère also indicates another path to the same conclusion. In the "Mémoire sur les effets," the earliest memoir absolutely attributable to Ampère, he describes what seem to be his earliest experiments. What he saw, which had escaped Oersted, was that a compass needle

[25] Quoting "Analyse," p. 239 (= "Suite du Mémoire," ¶2). The account of this first discovery in "Suite du Mémoire" (pp. 198ff) is much more detailed, in spite of Ampère's insistence that it records what he said 18 Sept. Most probably, the "Analyse" is what he read, for he was just presenting results: his ideas on the nature of magnetism were still embryonic and he did not then share them with the Académie. In the later memoir the ideas have matured and he does report on them, so that the account is much more detailed and substantial.

[26] "Analyse," p. 241.

was a detector of an electric current. This new instrument he named a galvanometer, and he immediately proceeded to use it to map the electric current in his voltaic circuit. To his great surprise, he discovered that a current flowed through the pile as well as through the conjunctive wire, a result that was in absolute contradiction to the theory of the pile then current in France. According to this theory, whose primary proponent was J.-B. Biot, the contact of dissimilar metals caused the electric fluids in the pile to separate. This separation was manifested by electrostatic tension at each pole of the pile, and the "current" was the discharge of these tensions through the conjunctive wire.[27]

When he first detected the current through the pile, Ampère was very careful to make sure that the effect was real and that a current did pass through the pile itself. He built a special pile that guarded against any source of experimental error—"une pile à auges dont les plaques de zinc soient soudées à celles de cuivre par toute l'étendue d'une de leurs faces, et non pas simplement par une branche de métal qu'on pourrait regarder avec raison comme une portion de conducteur."[28] This discovery that a current passed through the pile was Ampère's second important discovery. By mapping the entire circuit, Ampère thus completed what Oersted had begun.

This discovery now permitted him to attack the electrostatic theory of the pile. There is no mention of such attacks in the reports of the 18 September meeting; one suspects that these were added somewhat later, for they do appear in the "Mémoire sur les effets" of 2 October.

The simple experiments that Ampère did to convince himself that the electrostatic theory of the pile was incorrect underlined the importance of his earlier conclusion that the compass needle or galvanometer always was the best indicator for the flow of current through the voltaic circuit. Thus, when the ends of the conjunctive wire were placed in pure water, there was little or no decomposition and little or no deviation of the needle. When a bit of nitric acid was added, the decomposition was vigorous, and so was the action of the galvanometer. Obviously, Ampère concluded, the addition of nitric acid could have no effect on the tensions in the pile; rather, it permitted a current to flow, and this was the important factor.[29]

These tests of the electrostatic theory gave birth to a speculation and, possibly, to an experiment of fundamental importance to the development of Ampère's ideas on the nature of magnetism. Hitherto, the flow of an electric current had been detected by the imposition of something in the circuit, a decomposable liquid or a human tissue like the tongue. The new galvanometer could detect currents *in situ* without affecting the currents themselves. Suppose, Ampère suggested, that a pile were made in the form of a circle, then "il est assez évident,

[27] "Mémoire sur les effets," pp. 67 (galvanometer), 68 (current through the pile). For the theory of the pile, see Theodore M. Brown, "The Electric Current in Early Nineteenth-Century French Physics," *Historical Studies in the Physical Sciences,* 1969, *1*:61–103.

[28] "Mémoire sur les effets," p. 68, n. 1.

[29] *Ibid.*, pp. 65ff. Caneva, "Ampère," p. 133, n. 19, notes that Brown says that "Ampère was originally a defender of the 'electrostatic theory' of the pile," for which I can find no evidence. What Brown says, "Electric Current," p. 84, is that "Ampère confronted Oersted's phenomenon with the basic assumptions of the electrostatic theory clearly in mind." It is curious that Brown does not see the implications of Ampère's discovery—that the current passes through the pile itself. Instead, he is deflected by Ampère's theory of the electric current and fails to realize that Ampère had raised a major challenge to the electrostatic theory.

d'après les observations précédentes, qu'une pareille pile ne pourrait produire en aucun de ses points ni tensions ni attractions ou répulsions électriques ordinaires, ni phénomènes chimique, puisqu'il est impossible d'interposer un liquide dans le circuit."[30]

Did Ampère construct such a circular pile? At the end of the memoir supposedly presented to the Académie on 2 October, he compares the terrestrial currents he has hypothesized in paragraph 3 of the "Analyse" to those that "would" exist in a circular pile. "Ce courant, s'il existe, doit être comparé à celui que j'ai montré dans la pile agir sur l'aiguille aimantée, comme se dirigeant de l'extrémité cuivre à l'extrémité zinc, quand on établissait un conducteur entre elles, et qui aurait lieu de même si, la pile formant une courbe fermée, elles étaient réunies par un couple semblable aux autres."[31] In the *Exposé* the language is more positive: in discussing the current that he supposed to flow in a little section of a permanent magnet, Ampère mentions a circular pile as though it really existed (see Fig. 1).

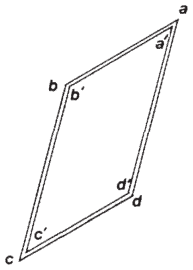

Figure 1

Supposons donc qu'il existe, dans le contour *abcd* de cette tranche, le même état électrique qui a lieu dans une pile dont les deux pôles sont en communication, comme, par exemple, si toutes les molécules de *a* en *b*, de *b* en *c*, etc., s'enlevaient l'une à l'autre l'électricité positive de manière à la transporter suivant *abcda*, et l'électricité négative en sens contraire, exactement comme la chose a lieu dans une pile circulaire, dont les deux pôles se rejoignent, ou dans une pile ordinaire dont les deux pôles sont en communication par un fil métallique.[32]

Such a pile would not have been difficult to construct, since it only involved placing the various elements in a circle. What is important is that the actual construction was not necessary for Ampère's ideas. What he had been led to was a circular current that manifested itself *only* by its action on a compass needle. But this is exactly what happens with the earth. A compass needle is deviated, and this must then mean that there are electrical currents that circulate in the earth. These currents look very much like a circular pile. They exist "comme une ceinture continue tout autour de la terre."[33] Ampère quite specifically restricts this "ceinture" to the equatorial regions so that the "belt" is completely analogous to a circular pile.[34]

The final link in Ampère's chain of argument now seemed obvious.

> Maintenant, si des courans électriques sont la cause de l'action directrice de la terre, des courans électriques seront aussi la cause de celle d'un aimant sur un autre aimant; d'où il suit qu'un aimant doit être consideré comme un assemblage de courans électriques qui ont lieu dans des plans perpendiculaires à son axe, dirigés de manière que le pole austral de l'aimant, qui se porte du côte du nord, se trouve à droite de ces courans, puisqu'il est toujours à gauche d'un courant placé hors de l'aimant, et

[30] "Mémoire sur les effets," p. 75.
[31] "Suite du Mémoire," p. 203.
[32] Riffault, *Supplément*, p. 198; *Exposé*, p. 33.
[33] "Suite du Mémoire," p. 203.
[34] "Notice sur les expériences lue le 2 avril 1821," (cit. n. 17), p. 20. Ampère mentions the "ceinture" in "Analyse," p. 241; therefore his work on the mapping of piles and his concept of the circular pile date from before 18 Sept.

> qui lui fait face dans une direction parallèle, ou plutôt ces courans s'établissent d'abord dans l'aimant suivant les courbes fermées les plus courtes, soit de gauche à droite, soit de droite à gauche, et alors la ligne perpendiculaire aux plans de ces courans devient l'axe de l'aimant, et ses extrémités en font les deux pôles.[35]

When did Ampère enunciate this theory of magnetism? Not on 18 September, for we know that he did not have the time to complete the reading of his memoir, and this part had to be deferred until 25 September. It was, therefore, at the beginning of his presentation on 25 September 1820 that Ampère put forth his theory that permanent magnets were caused by electrical currents within them circulating around the axis.

It is now time to return to the second result of his experiments that Ampère announced to the Académie on 18 September.

> 2me résultat; action attractive ou répulsive. Lorsqu'un courant galvanique et un aimant sont à angle droit, ils s'attirent, si le pôle nord est à gauche du courant, c'est-à-dire si la position est celle que le conducteur et l'aimant tendent à prendre en vertu de leur action mutuelle; ils se repoussent si le pôle nord de l'aimant est à la droite du courant, c'est-à-dire si le conducteur et l'aimant sont maintenus dans la position opposée à celle qu'ils tendent à se donner mutuellement.[36]

In "Suite du Mémoire" Ampère pointed out that Arago, when he heard of Ampère's successful experiment demonstrating these effects, told him that they followed directly from Oersted's paper. In particular, they could be deduced from the passage that Ampère quotes as follows: "Posito autem filo (cujus extremitas superior electricitatem a termino negativo apparatus galvanici accipit) e regione puncto inter polum et medium acus sito, occidentem versus agitur." Thus, according to Arago, the fact "when the wire is opposite to a point between the pole and the middle of the needle, the pole is [moved] towards the west" leads directly to the recognition of attractions and repulsions of the entire needle. For, as Ampère immediately noted, "ce mouvement de l'aiguille aimantée, indiqué comme ayant lieu soit que le conducteur se trouve à l'occident ou à l'orient de l'aiguille, est dans le premier cas une attraction, parce que le pole austral est à la gauche du courant, et dans le second un répulsion, parce qu'il se trouve à droite."[37] Ampère, however, did not follow this path. Instead, he insisted, as the "Analyse" reported, that he based his second discovery on the deduction of the explanation of magnetic phenomena, "fondée sur l'existence des courans électriques dans le globe de la terre et dans les aimans, que cette explication me conduisit au second résultat général, et me suggéra, pour le constater, une experience qui réussit complètement." The experiment consisted in hanging a magnetized needle vertically by a silk thread. A wire ran, at right angles to the

[35] "Suite du Mémoire," p. 207; see also "Analyse," p. 242.

[36] *Ibid.*, p. 238.

[37] "Suite du Mémoire," p. 201, citing Oersted, "Experimenta"; see Oersted, *Scientific Papers*, ed. Mayer, Vol. II, p. 217; Eng. trans. from John Christian Oersted, "Experiments on the Effect of a Current of Electricity on the Magnetic Needle," *Annals of Philosophy*, 1820, *16*:275. My colleague Brian Tierney pointed out to me the correction of "moved" for "most." Ampère's Latin poses another bibliographical problem: the passage in parentheses does not appear in Oersted's paper. Did Ampère have a different copy? Or, more likely, did he simply interpolate this Latin phrase to make the meaning clear, without concerning himself about the exact quotation? If this is the explanation, it reinforces my warnings about taking Ampère literally in his historical scholarship.

needle, by the middle of the needle. When a current passed in the wire, the needle was either attracted or repelled; when the current direction was reversed, so, too, was the attraction or repulsion.[38]

We are now almost done with our consideration of the memoir that Ampère read to the Académie on 18 September. We know what he read with some precision and we have reconstructed a probable course of the ideas behind the memoir. There remains one further task: to reconcile all this with what Ampère himself wrote about the occasion. In the "Notes" to Hachette's article he gives quite a different account from that presented here.

Séance du 18 septembre 1820

> Je réduisis les phénomènes observés par M. Œrsted à deux faits généraux. Je montrai que le courant qui est dans la pile, agit sur l'aiguille aimantée comme celui du fil conjonctif. Je décrivis les expériences par lesquelles j'avois constaté l'attraction ou la répulsion de la totalité d'une aiguille aimantée par le fil conjonctif. Je décrivis les instrumens que je me proposois de faire construire, et, entre autres, des spirales et des hélices galvaniques. J'annonçois que ces dernières produiroient, dans tous les cas, les mêmes effets que les aimans. J'entrai ensuite dans quelques détails sur la manière dont je conçois les aimans, comme devant uniquement leurs propriétés à des courans électriques dans des plans perpendiculaires à leur axe, et sur les courans semblables que j'admets dans le globe terrestre; en sorte que je reduisis tous les phénomènes magnetiques à des effets purement électriques.[39]

None of our earlier sources agree with this statement. The independent reports in the *Bibliothèque universelle* and in the *Annales générales des sciences physiques* are in perfect accord with both the "Analyse" and our account. They mention the two discoveries, and that is all. Only the "Note sur les expériences électro-magnetiques" in the *Annales des mines* repeats Ampère's claim to have discussed spirals and helices and his new theory of magnetism on 18 September.[40] "Repeats" is the proper term, for the language is almost exactly as that used by Ampère in "Notes," and I think it safe to conclude that this was the source for that account. Nevertheless, I do not think it proper either to ignore Ampère or to suggest that he was lying. What I suspect happened was that time ran out as he tried to read his memoir and that he hastily and with great confusion threw out to his audience some disjointed remarks on spirals and helices and on magnetism that no one understood or felt worth taking down. Still, there is an important point to be made. Although we know that the basic idea of the nature of magnetism as electricity in motion was in Ampère's head by 18 September, we can be equally certain that he did not convey that idea to anyone else at the time. It was not until 25 September that he was able to develop his theory in some detail and support it with striking experimental evidence.

[38] "Analyse," p. 240; "Suite du Mémoire," pp. 201–202 (quoting p. 201). I must confess, here, to being unable to follow Ampère's reasoning from terrestrial currents to these attractions and repulsions. It was *not* the result of his having discovered the attractions and repulsions of two electrical currents, for this came later. It would appear to follow from the orientation of the needle with respect to the wire, but I cannot see how this was translated into attraction or repulsion. Perhaps some other Ampère scholar can provide this important link in Ampère's chain of reasoning.

[39] "Notes," p. 166.

[40] "Note sur les expériences," p. 539.

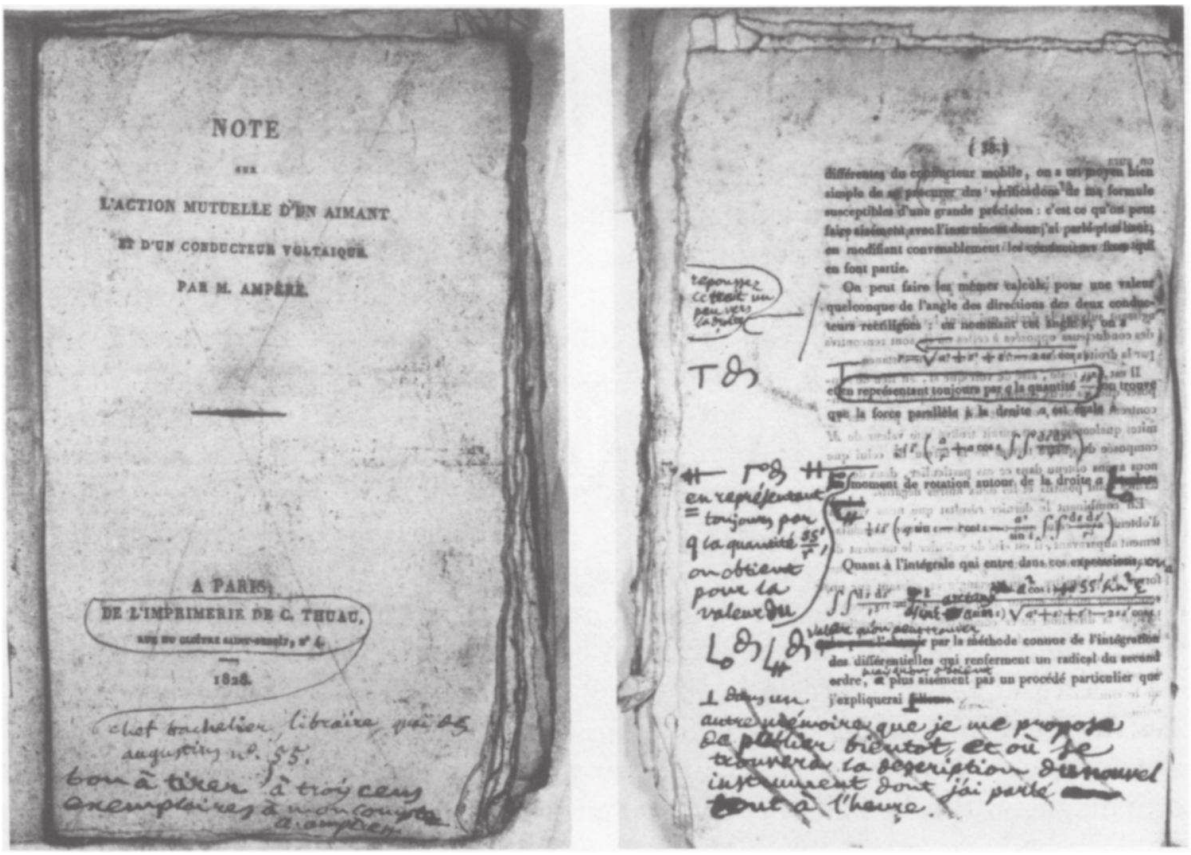

Figure 2. *Later version of Ampère's memoir, showing his practice of revising his text. Photo courtesy of Alain Brieux, Paris.*

We can follow Ampère rather clearly through the week between 18 and 25 September. Writing his son on 25 September, he remarked: "Je lus le commencement d'un mémoire à la séance de lundi il y a aujourd'hui huit jours. Je fis les jours suivants, tantôt avec Fresnel, tantôt avec Despretz, les expériences confirmatives; je les répétai toutes vendredi soir chez Poisson."[41] On Tuesday, Wednesday, and Thursday (19, 20, and 21 September) Ampère experimented with Fresnel and Despretz, trying to find experimental evidence for his new ideas on the nature of magnetism. He tried first to imitate the action of a permanent magnet by means of a current-carrying helix: "La manière dont je conçois l'aimant comme un assemblage de courans électriques dans des plans perpendiculaires à la ligne qui en joint les poles, me fit d'abord chercher à en imiter l'action par des conducteurs pliés en hélice, dont chaque spire me représentait un courant disposé comme ceux d'un aimant." With such a helix, wound around a glass tube and suspended in the middle "comme l'aiguille d'une boussole," Ampère hoped to show the interaction of the electric current in the helix with a permanent magnet and then with the magnetic field of the earth. The first succeeded, the second failed.[42] Encouraged by his partial success, Ampère turned to two experiments he was convinced would be decisive. He does not tell us what they were, but we can reconstruct them from his letter to his son. "L'expérience décisive que j'avais conçue comme preuve définitive exigeait deux piles galvaniques; tentée avec des piles trop faibles chez moi avec Fresnel,

[41] Ampère to J.-J. Ampère, 19–25 Sept., *Correspondance*, Vol. II, p. 562.
[42] "Suite du Mémoire," p. 172.

elle n'avait point réussi." He took two helices and connected the ends of each to two voltaic piles, obviously hoping to observe them attract and repel one another just as two magnets, placed parallel to one another, would do. He attributed his failure to achieve an effect to the weakness of the piles. He did the same thing with two spirals, that is, two wires wound in the same plane to give roughly circular currents when connected to a pile. Again the results were disappointing. On Sunday, 24 September, he persuaded Dulong to permit him to buy a large and powerful pile that the instrument maker Dumotier had made for the Faculty of Sciences at Paris. "Ce matin [25 September], l'expérience a été faite chez Dumotier avec un plein succès et répétée aujourd'hui à 4 heures à la séance de l'Institut."[43]

Once again, we must correct Ampère's account, for it contradicts what he wrote elsewhere. The experiment was not "un plein succès" in the sense that he got all the results he wanted; it was, in the sense that one of the results fully confirmed his electromagnetic hypothesis. He repeated the experiments with a helix and a magnet, and got the same results, only more powerfully. When he substituted a spiral for the helix, again he got what he expected—an interaction between the current-carrying wire wound in a circle and a permanent magnet. But the real proof Ampère was looking for involved the elimination of all magnets entirely. Thus he took two helices and hoped to show that they acted just like magnets. But he had only the one pile. He immediately saw that both helices could be connected to the same pile with no effect on the results, and this he did.[44] He was stunned by the results. Because his helix was made of bare wire, it was very loosely wound so that it was quite long relative to the number of turns of wire. When two such helices were opposed along their lengths and a current passed through both of them, Ampère expected to get strong repulsions when the currents were in the same direction, and strong attractions when they were in opposite directions. Currents in the same directions would, he thought, create "magnets" with similar poles opposite one another and the result would be repulsion; attraction would accompany the formation of dissimilar poles from the dissimilar currents. Instead, he got rather weak attractions when the currents were in the same direction, "phénomène qui m'étonnait beaucoup avant que j'en eusse découvert la cause."[45] Since he could not discover the cause before the meeting of the Académie that afternoon, Ampère simply dropped all mention of helices, even the experiment with a helix and a magnet, until he was able to understand why they had acted anomalously. He described instead his experiments with spirals, which had succeeded brilliantly in the morning, and repeated them. A spiral attracted or repelled the poles of a bar magnet, depending on the direction of the current through it.[46] More importantly, two spirals attracted or repelled one another; when the currents were in the same direction, they attracted and when they were in opposite directions, they repelled mutually.[47]

Ampère's announcement of his discovery has caused great confusion among

[43] Ampère to J.-J. Ampère, 19–25 Sept., p. 562.

[44] "Analyse," p. 244, explains the virtues of using only one pile. See also "Mémoire sur les effets," p. 72.

[45] "Suite du Mémoire," p. 176.

[46] *Ibid.*, p. 208.

[47] See the accounts in *Bibl. universelle*, 1821, *17*:83; *Annales générales des sciences physiques*, 1820, *6*:129; and "Notes," p. 166.

historians of science ever since. In "Suite du Mémoire," he wrote: "En remplacant l'aimant par une autre spirale dont le courant soit dans le même sens que le sien, on a les mêmes attractions et répulsions; c'est ainsi que j'ai decouvert que deux courans électriques s'attiraient quand ils avaient lieu dans le même sens, et se repoussaient dans le cas contraire."[48] But he wrote this after he had discovered the effects of two current-carrying, parallel, straight wires on one another, and it is possible that he may have confused the two discoveries. Certainly what he discovered and reported on 25 September was that currents in *parallel planes* reacted upon one another. For at least one week he had been thinking of *circular* currents as producing magnetic poles, and it was a logical consequence of this concept that two circular spirals should attract and repel one another. But this was not the same thing as attractions and repulsions between two rectilinear current-carrying wires. That on 25 September Ampère was not referring to this latter effect is easily proven, for on 9 October he did report it. As he put it in "Notes," "Je montrai, sur deux courans électriques rectilignes, les mêmes effets que j'avois montrés dans la séance précédente sur des courans dans des conducteurs pliés en spirales."[49]

The process by which Ampère was moved to investigate rectilinear current-carrying wires was probably as follows. At the meeting of the Académie on 25 September, Arago showed an experiment in which iron filings were magnetized by a current-carrying wire.[50] When he asked Ampère how to magnetize a long needle, Ampère suggested putting it inside a glass tube around which a helix was wound. When the experiment was tried, it worked perfectly.[51] The needle was strongly magnetized.

The success of this experiment, the fact that a helix carrying a current acted like a magnet, and the failure of two current-carrying helices to attract and repel one another as Ampère expected could not help but focus Ampère's attention on this latter anomaly. His theory worked in the first two cases but failed notably in the last. Why? Ampère does not tell us what chain of thought led him finally to the solution, but one clue offers some light. The footnote that Riffault placed at the very beginning of the *Exposé,* which seems to have been provided by Ampère himself, describes a peculiar effect. After pointing out that Ampère had originally begun his work to complete what Oersted had begun, the note goes on: "Mais bientôt il découvrit lui-mème, qu'une autre portion du circuit voltaique exerçait, sans la présence d'aucun aimant, une nouvelle sorte d'action sur le fil métallique au moyen duquel ce circuit est établi."[52] It is possible to date when this effect of part of the circuit on another part could have been observed. It takes fairly strong currents to move the wires in a circuit. Before Ampère bought Dumotier's pile on 25 September, he had only feeble apparatuses at his disposal, in which the currents would have been far too weak to cause attractions and repulsions that would catch anyone's attention. But the experimental set-up with the spirals that he demonstrated at the Académie on September 25 was ideal to show this "nouvelle sorte d'action." "J'ai imité cette

[48] "Suite du Mémoire," p. 208.

[49] "Notes," p. 167. Again note Ampère's carelessness in matters of chronology. It was not in the preceding session, 2 Oct., but the one before, 25 Sept., that he had demonstrated his spirals.

[50] Account in *Bibl. universelle,* 1821, *17*:82.

[51] Riffault, *Supplément,* pp. 233–234; *Exposé,* pp. 68–69.

[52] Riffault, *Supplément,* p. 168, n. 1; *Exposé,* p. 1, n. 1.

disposition autant qu'il était possible avec un courant électrique, en en pliant le fil conducteur en spirale: cette spirale était formée avec un fil de laiton et terminée par deux portions rectilignes de ce même fil, qui étaient renfermées dans deux tubes de verre, afin qu'elles ne communiquassent pas entre elles, et pussent être attachées aux deux extremités de la pile.''[53] The lead wires were so close together that they had to be encased in glass tubes to prevent a short circuit. Under these conditions, when the connection was made to the poles of the pile, these two wires must have jumped apart rather smartly. The effect is easily produced with currents of 10 amperes or more, and can hardly be missed.

When did Ampère notice the effect? The ''Analyse'' reports that Ampère observed attractions and repulsions of rectilinear current-carrying wires and demonstrated them before the Académie ''après avoir terminé la lecture de son mémoire'' on 25 September.[54] In ''Notes,'' however, there is no mention of the effect, and it seems hardly likely that Ampère would forego putting such an important discovery into his account. The two accounts can be reconciled by supposing that Ampère did notice the effect as he demonstrated his spirals to the Académie, but did not fully understand what was going on at the time. Thus, he could show the effect to the Académie but not consider it a discovery until after he had experimented more carefully and found the general laws of the interaction. Between 25 September and 9 October that seems to be what he did. He built his famous apparatus which demonstrates the effect and carefully studied it. On 9 October he announced his results to the Académie.[55]

The discovery of the effect of two rectilinear, current-carrying wires on one another provided the solution to the anomalous behavior of the two helices. Because the helices were so loosely wound, the longitudinal effect of the currents overpowered the magnetic effect of the circular ''spires.'' Thus, when the currents in the two helices were in the same directions, the longitudinal effect caused an attraction more powerful than the magnetic repulsions created by the formation of adjacent, similar magnetic poles in the helices. This explanation, incidentally, is the source for Ampère's famous experiment in which he showed that the attractions and repulsions of two wires depended solely on the lengths over which they acted, and not on the kinks, curves, or other deformations of the wires between their two ends.

Armed with this explanation, Ampère could now easily correct his experiment. Ironically, the solution was found in an arrangement that he had given to his helix when he had tested it against a permanent magnet. The suspension on a fine point was too delicate, and Ampère had changed his arrangement so that the helix was actually suspended on its own wire. This he did by running the wire down the center of a glass tube, then winding the wire back to the center, around the other arm of the helix, and then back down through the center again, so that the whole helix could turn relatively freely on the suspending wire. If two helices were wound in this way, with the wire forming the helix passed down through the glass tube, then the two longitudinal parts of this wire cancelled one another out, permitting the magnetic effect full play. On 6 November

[53] ''Suite du Mémoire,'' p. 207.
[54] ''Analyse,'' p. 242.
[55] ''Notes,'' p. 167. For the apparatus see ''Mémoire sur les effets,'' Fig. 1 and p. 71.

Ampère announced this solution to the problem to the Académie and also demonstrated how a helix could reproduce the actions of a permanent magnet.[56]

Ampère was now, finally, in a position to "prove" that permanent magnetism was the result of closed, electrical currents in the body of the bar magnet. Knowing that two current-carrying wires attracted or repelled one another depending on the directions of the currents, he could find the actual direction of rotation of the currents in the magnets. These currents, he then demonstrated, followed his general law.

> Il suit de la situation des courans électriques dans toute la masse d'un aimant, qu'à ses extrémités, ces courans se meuvent dans des courbes formées autour de chaque pôle; que quand on en présente au milieu d'un conducteur rectiligne mobile, que M. Ampère suppose horizontal, de manière que l'axe de l'aimant soit dans le plan de ce conducteur, il ne peut avoir aucune action pour le mouvoir; mais que dès qu'on l'élève au-dessus de ce plan ou qu'on l'abaisse audessous, le courant électrique rencontre d'un côté, des courants dans l'aimant qui se meuvent dans le même sens et l'attirent, et de l'autre, des courans qui se meuvent dans le sens opposé et le repoussent. C'est ce que confirme l'expérience.[57]

How satisfying this experiment must have been for Ampère. He had started his researches to complete what Oersted had begun. A magnetic needle could be used to map electric currents; now Ampère could show that electric currents could be used to map magnetic needles.

The discovery of the attractions and repulsions of rectilinear, current-carrying wires marks the end of Ampère's early discoveries in electrodynamics. This discovery, he realized, was the basic one to which he could relate all his earlier results. It formed the "fait primitif" upon which he insisted a science must be based and it also provided him with a starting point for the mathematization of his physical hypothesis on the nature of magnetism.[58] The physics was complete. What remained for Ampère to do was to mathematize his results and account for currents in permanent magnets. But that is another story.

APPENDIX. THE BIRTH OF ELECTRODYNAMICS: A BRIEF CHRONOLOGY OF DISCOVERIES AND IDEAS

1820	
4 September	Arago announces Oersted's discovery to the Académie.
11 September	Arago reproduces Oersted's experiments.
5–17 September	Ampère discovers that the compass needle sets at right angles to the current-carrying wire when the effect of terrestrial magnetism is eliminated. He also maps the entire voltaic circuit and finds that the current travels through the pile as well. Investigation of the characteristics of a circular pile leads him to his theory that electricity

[56] "Notes," p. 168.

[57] "Analyse," p. 246.

[58] For the *fait primitif* see Ampère to Speyer van der Eyk, 15 Aug. 1821, *Correspondance*, Vol. II, p. 570, ¶4. For Ampère's basic idea on which his calculations depended, see "Suite du Mémoire," p. 174. The best discussion of Ampère's philosophy of science in general and the notion of a *fait primitif* in particular is to be found in James R. Hofmann, "The Great Turning Point in André-Marie Ampère's Research in Electrodynamics: A Truly 'Crucial' Experiment" (Ph.D. diss., Univ. Pittsburgh, 1982), pp. 127ff.

	in motion produces magnetism and that permanent magnets must contain electrical currents.
18 September	Ampère uses the astatic needle to illustrate deflection of the compass needle before the Académie. He also does an experiment with a vertical, magnetized needle to show attraction and repulsion of the needle, as a whole, by a current-carrying wire. At the end of his lecture, he may well have mentioned helices and spirals, which he will use to prove his theory of magnetism.
19–21 September	Working with Fresnel, Ampère fails to get magnetic effects from helices and spirals.
25 September (morning)	Using Dumotier's powerful pile, Ampère experiments with helices and gets anomalous results. He tries spirals and gets strong attractions and repulsions between a spiral and a magnet and then between two spirals connected to the same pile.
25 September (afternoon)	Ampère finishes reading the memoir begun 18 September before the Académie, and offers his theory of magnetism as electricity in motion. He applies the theory to terrestrial magnetism. He repeats the morning experiments with spirals. He probably sees the leads twitch when the current is turned on, and thus suspects the interaction of one segment of a current-carrying wire with another. After the lecture, he witnesses Arago's magnetization of iron filings by a current-carrying wire and suggests using a helix to magnetize a needle. The experiment is done and is successful.
25 September–2 October	Ampère picks up the clue offered by the twitch of the leads and discovers the attractions and repulsions of rectilinear, parallel current-carrying wires. He composes the memoir presented to the Academy on 2 October and later published in the *Annales de chimie et physique*.
9 October	Ampère demonstrates the actions of rectilinear current-carrying wires before the Académie. He insists upon the insufficiency of the old theory of the pile by drawing attention to the quite different character of the attractions and repulsions of currents, as opposed to ordinary (static) attractions and repulsions.
16 October	Ampère reads a note relative to Arago's magnetization of a long wire and shows how it is perfectly consistent with his theory. (Not discussed in article).
30 October	Ampère announces the discovery of the directive power of the earth's magnetic field on two apparatuses that he used to demonstrate the effect of the terrestrial field on electric currents (not discussed in article).
6 November	Ampère announces his solution of the problem of the interaction of two parallel, current-carrying helices by bringing a wire leading away from each helix down through the middle of the helix to cancel the longitudinal effect. He then shows how such a helix acted exactly like a compass needle.